HAPTIC DEVICES HAVING MULTIPLE OPERATIONAL MODES INCLUDING AT LEAST ONE RESONANT MODE

CROSS-REFERENCE TO RELATED PATENT APPLICATIONS

[1001] This application is a continuation-in-part and claims priority to U.S. Patent Application No. 10/301,809, entitled "Haptic Feedback Using Rotary Harmonic Moving Mass" and filed November 22, 2002; and U.S. Patent Application No. 60/375,930, entitled "Haptic Feedback Using Rotary Harmonic Moving Mass" and filed April 25, 2002; the disclosure of both being incorporated by reference.

FIELD OF THE INVENTION

[1002] The invention relates generally to the application of vibrotactile feedback. More particularly, the invention relates to a haptic feedback device having multiple operational modes including multiple resonant modes.

BACKGROUND OF THE INVENTION

[1003] Generally, electro-mechanical transducers exhibit a level of power consumption that may be higher than desired. Furthermore, such electro-mechanical transducers may not be able to produce haptic feedback of a desired magnitude or bandwidth due to space constraints.

[1004] What is needed is an electro-mechanical transducer that is configured to produce vibrotactile feedback having a relatively high magnitude and/or an adjustable bandwidth. Additionally, it would be desirable to have an electro-mechanical transducer that can generate haptic feedback having relatively low energy consumption.

SUMMARY OF THE INVENTION

[1005] An apparatus comprises a signal source, a driver and an electro-mechanical transducer. The signal source is configured to output a haptic feedback signal. The driver is configured to receive the haptic feedback signal and output a drive signal. The electro-mechanical transducer is configured to receive the drive signal. The electro-mechanical transducer is configured to have a set of operational modes. Each operational mode from the set of operational modes has at least one resonant mode from a set of resonant modes.

BRIEF DESCRIPTION OF THE DRAWINGS

[1006] Fig. 1 is a system block diagram of an electro-mechanical transducer, according to an embodiment of the invention.

[1007] Fig. 2 shows a perspective view of an electro-mechanical device according to an embodiment of the invention.

[1008] Fig. 3 shows a perspective view of an electro-mechanical transducer according to an embodiment of the invention.

[1009] Fig. 4 shows a perspective view of an electro-mechanical transducer according to another embodiment of the invention.

[1010] Fig. 5 shows a perspective view of an electro-mechanical transducer in a parallel arrangement, according to an embodiment of the invention.

[1011] Fig. 6 illustrates a plot of a gain profile for a single resonant mode output from single electro-mechanical transducer according to one embodiment of the invention.

[1012] Fig. 7 illustrates a plot of a gain profile for multiple resonant modes output by an electro-mechanical transducer according to an embodiment of the invention.

[1013] Fig. 8 shows a perspective view of an electro-mechanical transducer in a series arrangement according to another embodiment of the invention.

[1014] Fig. 9 shows a side view of an electro-mechanical transducer shown in Fig. 8 in a rest position.

[1015] Fig. 10 illustrates the electro-mechanical transducer according to the embodiment depicted in Fig. 8 operating in a first resonant mode.

[1016] Fig. 11 illustrates the electro-mechanical transducer according to the embodiment depicted in Fig. 8 operating in a second resonant mode.

[1017] Fig. 12 illustrates the electro-mechanical transducer according to the embodiment depicted in Fig. 8 operating in a third resonant mode.

[1018] Fig. 13 is a flow chart illustrating a method for producing an operational mode of an electro-mechanical transducer according to an embodiment of the invention.

DETAILED DESCRIPTION

[1019]

[1020] An apparatus comprises a signal source, a driver and an electro-mechanical transducer having a cantilever. The signal source is configured to output a haptic feedback signal. The driver is configured to receive the haptic feedback signal and output a drive signal. The electro-mechanical transducer has a cantilever and is configured to receive the drive signal. The electro-

mechanical transducer is configured to have a set of operational modes. Each operational mode from the set of operational modes has at least one resonant mode from a set of resonant modes.

[1021] In one embodiment, electro-mechanical devices are used in an electro-mechanical transducer that is configured to output haptic feedback in an operational mode having one or more resonant modes. The electro-mechanical transducer is also configured to have multiple operational modes. Such a device can produce diverse and robust haptic feedback that can exhibit relatively low power consumption in a space-efficient manner. Although many embodiments described herein relate to using cantilevers as resonant structures, analogous devices are also possible. For example, such resonant structures can use acoustic cavities, membranes, mass-springs, wheel-torsional springs, and/or other structures capable of exhibiting mechanical resonance. Some embodiment, for example, can have a combination of different types of structure capable of exhibiting mechanical resonance.

[1022] As used herein, the term "operational mode" means a method or manner of functioning in a particular condition at a given time. For example, if a first electro-mechanical device is operating in a first resonant mode and a second electro-mechanical device is operating in a second resonant mode, the electro-mechanical transducer is operating collectively in, for example, a first operational mode. Alternatively, for example, if the first electro-mechanical device is operating in a third resonant mode, and the second electro-mechanical device is operating in a fourth resonant mode, the electro-mechanical transducer is operating collectively in a second operational mode. In another example, if the first electro-mechanical device is operating in a first resonant mode, and the second electro-mechanical device is not operating, the electro-mechanical transducer is operating collectively in a third operational mode. In other

words, a given operation mode can be based on one electro-mechanical device operating in a resonant mode and another electro-mechanical device not being activated.

[1023] The term "resonant mode" means any mode of an electro-mechanical device operating in a frequency band centered around a resonant frequency. When an electro-mechanical device operates at or near a resonant frequency, several consequences occur. For example, when a transducer operates at or near a resonant frequency, the inertial term and the elastic terms substantially cancel. The power consumed by the actuator is then dedicated to balance dissipation (e.g. damping). If the dissipation is low, for example, in a cantilevered piezo-electric beam (i.e. a resonator with a high Q factor), the displacement is relatively large and limited by dissipative forces. In addition, if the mass that resonates is comparable to the mass of the structure to which the transducer is attached (e.g. case of a telephone), then the structure vibrates with a relatively large magnitude. Power lost during activation is in the dissipation. The remaining power is transmitted to the anatomy of the person with which the device is in contact.

[1024] The term "electro-mechanical device" as used herein, means an individual active component configured to provide haptic feedback. The term "active component" refers to a single component that provides a mechanical response to the application of an electrical signal. For example, for the embodiment illustrated in Fig. 5 and discussed below, a single length of, for example, piezoelectric material (for example, piezoelectric bar 410) and the associated mass (for example, mass 412) is referred to herein as the electro-mechanical device. In the example illustrated in Fig. 8 and discussed below, the electro-mechanical transducer includes only one electro-mechanical device.

[1025] The term "electro-mechanical transducer" means an apparatus having one or more electro-mechanical devices coupled to a mechanical ground. For example, in the embodiment of

the invention illustrated in Fig. 5, the electro-mechanical transducer includes all three lengths of piezoelectric material, each having a mass coupled thereto. In the embodiment illustrated in Fig. 8, the electro-mechanical transducer includes piezoelectric bar 610 and the masses 620, 630, and 640.

[1026] An embodiment of an electro-mechanical transducer is illustrated in Fig. 1. An electro-mechanical transducer according to this embodiment of the invention includes a drive circuit 110 having an amplifier and includes an electro-mechanical transducer 120. The electro-mechanical transducer 120 includes one or more electro-mechanical (E-M) devices 121.

[1027] Drive 110 receives a haptic feedback signal and outputs a drive signal to electro-mechanical transducer 120. The haptic feedback signal may be based on a command from a microprocessor within, for example, a computer or a portable communications device (not shown). The electro-mechanical transducer 120 is configured to selectively operate in one of multiple possible operational modes at a given time. The operational mode of the electro-mechanical transducer 120 at a given time will depend, for example, on the characteristics of the drive signal received from driver 10. For a given operational mode, an electro-mechanical transducer can operate in multiple resonant modes as will be described in greater detail below. The one or more electro-mechanical devices 121 of electro-mechanical transducer 120 collectively output haptic feedback based on the drive signal, as illustrated in Fig. 7.

[1028] Fig. 2 illustrates a piezoelectric bar in accordance with one embodiment of the invention. As described below in more detail, such a piezoelectric bar can be used as an electromechanical device within an electro-mechanical transducer.

[1029] The piezoelectric bar 200 is a bimorph piezoelectric device that is a two-layer bending motor having a length (L) 220 substantially larger than a width (W) 210. In one embodiment,

the piezoelectric bar 200 has a width (W) 210 of approximately 0.6 mm, a length (L) 220 of approximately 25 mm and a height (H) 230 of approximately 5 mm. Alternatively, the piezoelectric bar can have any suitable dimensions depending on the desired use.

[1030] When a voltage 240 from, for example, a drive source (not shown), is applied across the piezoelectric bar 200, the piezoelectric bar 200 will flex. An appropriate level of voltage 240 to be applied to the piezoelectric bar 200 can be selected, based at least in part, on the material and the thickness of the material used to construct the piezoelectric bar 200.

[1031] The piezoelectric bar 200 can be driven near a resonant frequency. When the piezoelectric bar 200 is driven near a resonant frequency, impedance transformation may be obtained. Impedance transformation results in large mechanical displacements as described above.

[1032] An electro-mechanical device 300 that can be used in combination with other electro-mechanical devices to construct an electro-mechanical transducer is illustrated as Fig. 3. Multiple electro-mechanical devices 300 can be configured to operate in a selected operational mode from a set of possible operational modes, each operational mode having one or more resonant modes, as will be described in further detail with respect to Fig. 5.

[1033] The electro-mechanical device 300 illustrated in Fig. 3 includes a piezoelectric bar 310 having mass 320 coupled to an end portion 325 of the piezoelectric bar 310. A second end portion 335 of the piezoelectric bar 310 is coupled to a base member 330. Base member 330 acts as a mechanical ground and is configured to remain stationary relative to the movement of the piezoelectric bar 310.

[1034] The electro-mechanical device illustrated in Fig. 3 can operate as follows. A voltage 340 from a voltage source (not shown) can be applied to piezoelectric bar 310. The piezoelectric bar

can be, for example, a bimorph piezoelectric device as described above in connection with Fig. 2. Voltage 340 causes piezoelectric bar 310 to flex in a first direction D_1. Voltage 340 can be modulated at a frequency, f_d, which is referred to herein as the drive frequency of the electro-mechanical device 300. As described above, the frequency f_d can be selected such that the electro-mechanical device 300 operates near a resonant frequency the electro-mechanical device 300. Frequency f_d is a function of the type of electro-mechanical device used in the electro-mechanical transducer, the dimensions of the electro-mechanical device (e.g., the length, width, height or thickness), and the position and weight of the masses in the electro-mechanical device.

[1035] When the drive frequency f_d of the voltage 340 is such that the electro-mechanical device 300 operates near its resonant frequency, the electro-mechanical device 300 can produce a large vibration sensation relative to the voltage 340 applied to the electro-mechanical device 300.

[1036] Both the weight of mass 320 and the length of the piezoelectric bar 310 affect the amplitude of the displacement. Furthermore, the weight of mass 320 and the length of the piezoelectric bar 310 affect the resonant frequencies of the electro-mechanical device 300. Therefore, the particular resonant frequencies may be tailored by selecting the appropriate length of the piezoelectric bar and/or weight of the mass 320 for a desired resonant frequency. When voltage 340 is applied to the piezoelectric bar 310, the electro-mechanical device 300 will move in a plane oriented as vertical for the depiction in Fig. 3.

[1037] The embodiment illustrated in Fig. 4 is similar to that illustrated in Fig. 3. Fig. 4 shows an electro-mechanical device 350 including a piezoelectric bar 360 having mass 370 coupled to an end portion 375 of piezoelectric bar 360. The piezoelectric bar 360 has its second end portion 385 coupled to a base member 380, which acts as a ground and is configured to remain stationary with respect to movement of the piezoelectric bar 360.

[1038] The operation of the electro-mechanical device 350 is similar to the embodiment described with reference to Fig. 3 except that when voltage 390 is applied to piezoelectric bar 360, the electro-mechanical device 350 will vibrate in direction D_2 (i.e., relative to the perspective shown in Fig. 4) due to the orientation of the bimorph piezoelectric bar 360 relative to base member 380.

[1039] Fig. 5 illustrates an electro-mechanical transducer 400, according to another embodiment of the invention. The electro-mechanical transducer 400 includes three electro-mechanical devices 410, 420, and 430. In the illustrated embodiment, each of the electro-mechanical devices 410, 420 and 430 includes a piezoelectric bar 411, 421, and 431, respectively. A mass 412, 422, and 432 can be coupled to an end portion 413, 423, or 433, of each piezoelectric bar 411, 421 and 431, respectively. The second end portion 414, 424, and 434, of each piezoelectric bar 411, 421, and 431, respectively, is coupled to a base member 440. Base member 440 can be configured to remain stationary with respect to movement of the piezoelectric bars 411, 421 and 431. More specifically, base member 440 is stationary relative to any movement of piezoelectric bars 411, 421 and 431, but can move in the context of the overall product or device (e.g., mobile phone, game controller, etc.) with which the electro-mechanical device 400 is disposed. In fact, base member 440 can relay the vibrations produced by the movement of piezoelectric bars 411, 421 and 431 to the product or device. Base member 440 may be a single contiguous mechanical ground, as illustrated in Fig. 5. Alternatively, each piezoelectric bar 411, 421, and 431 may be coupled to a different mechanical ground.

[1040] Piezoelectric bars 411, 421, and 431 have lengths L1, L2, and L3, respectively. In one embodiment, these lengths may be the same. Alternatively, lengths L1, L2, and L3 can be different. Additionally, the weights of masses 412, 422, and 432, can be equal to one another.

Alternatively, weights of the masses 412, 422, and 432 can be different from one another. The particular configuration of the masses 412, 422 and 432 and the lengths of the piezoelectric bars 411, 421, and 431 can be based on the desired frequency response from the electro-mechanical transducer 400.

[1041] The operation of the electro-mechanical transducer in Fig. 5 will be described with reference to Figs. 4 and 5. Voltage 450 can be applied to the electro-mechanical devices through contacts 451. The voltage may by modulated at approximately the resonant frequency of the electro-mechanical devices 410, 420, and/or 430. The voltage may be applied by a single voltage source via contacts 451, or alternatively, each electro-mechanical device 410, 420, 430, may have an independent voltage source (not shown) that is modulated approximately at the resonant frequency of the respective electro-mechanical device, or a resonant mode of the respective electro-mechanical device. Alternatively, voltage 450 may be modulated at a higher order resonant frequency of the electro-mechanical devices 410, 420, and/or 430.

[1042] In an alternative arrangement, the electro-mechanical transducer 400 can include electro-mechanical devices 410, 420, and 430 that have different lengths L1, L2, L3. In this arrangement, each of the electro-mechanical devices 410, 420, and 430 has a different resonant frequency f_1, f_2, and f_3, respectively. These different resonant frequencies can be driven at different drive frequencies f_{d1}, f_{d2}, and f_{d3}. An example of the frequency response for an electro-mechanical transducer 400 is illustrated in Fig. 7. As depicted in the plot in Fig. 7, an electro-mechanical transducer with three electro-mechanical devices each operating at a different resonant frequency (or resonants thereof) has a frequency response with a greater bandwidth than the frequency response for an electro-mechanical transducer having a single electro-mechanical device, which is illustrated in Fig. 7. Note that the gain values shown on the y-axes in FIGS. 6

and 7 relate to the magnitude of the device position divided by the magnitude of the input voltage to the device.

[1043] In another arrangement, masses 412, 422, and 432 and lengths L1, L2, and L3 of electro-mechanical devices 411, 421, and 431 can be configured such that a single drive frequency, f_d, may be used to drive, for example, the resonant mode in electro-mechanical device 411, the first resonant mode in electro-mechanical device 422, and the second resonant mode in electro-mechanical device 432.

[1044] In yet another arrangement, the bandwidth of the electro-mechanical transducer 400 may be adjusted by selectively operating one or more of the electro-mechanical devices 410, 420, 430 in different resonant modes. Each one of these combinations of resonant frequencies collectively superpose into a different operational mode of the electro-mechanical transducer 400.

[1045] In a first operational mode, for example, the electro-mechanical transducer 400 can be operated such that electro-mechanical devices 410 and 430 may be operating at frequencies f_1 and f_3, respectively, with f_1 and f_3 being resonant modes of the electro-mechanical devices 410 and 430, respectively. A voltage need not be applied to electro-mechanical device 420 in this operational mode. In this operational mode, the output of the electro-mechanical transducer 400 would include peaks 510 and 530 illustrated in Fig. 7.

[1046] In a second operational mode, for example, the electro-mechanical transducer 400 can be operated such that electro-mechanical devices 410 and 420 are operating at frequencies f_1 and f_2, respectively, where f_1 and f_2 are resonant modes of the electro-mechanical devices 410 and 420. In this operational mode, the electro-mechanical transducer 400 can produce an output having only two peaks, as illustrated, for example, in Fig. 7 as 510 and 520. This operational mode can have two frequencies that are different from the two frequencies of the first operational mode

described above. Therefore, by changing the operational mode of the electro-mechanical transducer 400, the resultant frequencies of the tactile feedback can be changed.

[1047] In a third operational mode, for example, the electro-mechanical transducer 400 can be operated such that electro-mechanical devices 420 and 430 may be operating at frequencies f_2 and f_3, respectively, where f_2 and f_3 are resonant modes of each of the electro-mechanical devices 420 and 430. In this operational mode, the electro-mechanical transducer 400 can produce an output having only two peaks, as illustrated, for example, in Fig. 7 as 520 and 530. This operational mode can have two frequencies that are different from the two frequencies for first operational mode described above. Additionally, the third operational mode can have two frequencies that are different from the two frequencies of the second operational mode. Therefore, by changing the operational mode of the electro-mechanical transducer 400, the resultant frequencies of the haptic feedback can be changed.

[1048] In other operational modes, the electro-mechanical transducer 400 can be operated such that one of electro-mechanical devices 410, 420 and 430 is operating at frequencies f_1, f_2 and f_3, respectively, where f_1, f_2 and f_3 are resonant modes of each of the electro-mechanical devices 410, 420 and 430. In these operational modes, the electro-mechanical transducer 400 can produce an output having only one peak at a time. In other words, operational modes are possible where only a single electro-mechanical device is actuated at a given time.

[1049] The voltage can be modulated at a number of different drive frequencies, f_d. For example, the drive frequency f_d can approximate a resonant mode of the electro-mechanical devices. Alternatively, f_d can include any other frequency that is an integral multiple of the electro-mechanical device's resonant frequency.

[1050] While certain operational modes have been described with reference to Fig. 5, it will be apparent from this discussion that many other operational modes are possible. For example, by providing additional electro-mechanical devices, the number of possible operational modes increases. Additionally, while only three piezoelectric bars were illustrated in Fig. 5, any number of piezoelectric bars may be employed.

[1051] Additionally, while the embodiments were described above with reference to electro-mechanical devices that included piezoelectric bars, any electro-active material or device can be used. For example, the electro-mechanical devices can include electro-active polymers (EAP), voice coil transducers or other electro-magnetic device, an inertial resonant device, or a resonant eccentric rotating mass (HERM) device. An example of an inertial resonant device is described in co-pending U.S. Patent 6,088,019, which is hereby incorporated by reference in its entirety. An example of a HERM device is described in co-pending Patent Application Serial No. 10/301,809, which is hereby incorporated by reference in its entirety.

[1052] Fig. 8 illustrates an alternative embodiment of an electro-mechanical transducer 600 having multiple masses 620, 630, and 640 disposed on the same piezoelectric bar 610.

[1053] In this embodiment, electro-mechanical transducer 600 comprises one electro-mechanical device, the structure of which corresponds to the structure of electro-mechanical transducer 600. The piezoelectric bar 610 is secured to a base member 650, which acts as a mechanical ground and remains substantially fixed with respect to the movement of the electro-mechanical device 600. Masses 620, 630, and 640 can have equal weights or can have different weights. Alternatively, the weights of the two masses can be equal to one another, while the weight of the third mass can be different. Additionally, the masses 620, 630, and 640 can be equally spaced along the length of the piezoelectric bar 610 or can be spaced at any desired location along the

length of the piezoelectric bar 610. The weight of and spacing between masses 620, 630, and 640 allow the electro-mechanical device to be designed to have a predetermined number of resonant frequencies.

[1054] Next, the operation of the embodiment illustrated in Fig. 8 will be described with reference to Figs. 6-10. Figs. 7-10 illustrate an example of the different operational modes that can be obtained with an electro-mechanical transducer 600 bearing three masses. The bends in the piezoelectric bar 610 are exaggerated in this figure to illustrate the bending of the piezoelectric bar 610 more clearly.

[1055] Frequency modulated voltage can be applied to the piezoelectric bar 610. As illustrated in Fig. 9, the electro-mechanical device is initially in a resting position. Fig. 10 illustrates a first resonant mode of the electro-mechanical device. Fig. 11 illustrates a second resonant mode of the electro-mechanical device. Fig. 12 illustrates a third resonant mode of the electro-mechanical device. The modes illustrated in Figs. 7-10 will produce a resultant output having frequencies that are similar to the frequencies illustrated in Fig. 7 due to the superposition of the three resonant modes produced by the electro-mechanical device.

[1056] Fig. 13 illustrates a method for producing an operational mode of an electro-mechanical transducer, according to an embodiment of the invention. At step 1110, a haptic feedback signal is generated. At step 1120, the haptic feedback signal is supplied to a driver. At step 1130, the drive signal is then applied to a first electro-mechanical device. At step 1140, a drive signal is also applied to the second electro-mechanical device. At step 1150, the electro-mechanical devices output haptic feedback that includes haptic feedback at a first resonant mode (step 1151) and haptic feedback at a second resonant mode (step 1152). The output of haptic feedback at a first resonant mode by a first electro-mechanical device and/or at a second resonant mode by a

second electro-mechanical device correspond to an operational mode of the electro-mechanical transducer having the first electro-mechanical device and/or the second electro-mechanical device, respectively.

[1057] Additional electro-mechanical devices can be added and can have the drive signal selectively applied thereto to collectively yield a variety of different operational modes of the electro-mechanical transducer. Alternatively, the electro-mechanical transducer may include multiple masses, as illustrated in Fig. 8. By altering the frequency of the drive signal such that it substantially corresponds to the resonant frequencies of the electro-mechanical device, the electro-mechanical transducer can output haptic feedback having multiple frequencies for a given operational mode.

[1058] In another embodiment, a number of electro-mechanical devices in a serial configuration, as illustrated in Fig. 8, can be arranged in parallel as illustrated in Fig. 5.

[1059] The devices described above are capable of being used in small, portable devices where energy consumption needs to be low. For example, electro-mechanical transducers can be used in cellular phones, electronic pagers, laptop touch pads, a cordless mouse or other computer peripherals whether cordless or otherwise, a personal digital assistant (PDA), along with a variety of other portable and non-portable devices.

[1060] While the particular embodiments of the invention were described above with respect to piezoelectric bars, the invention is not limited to the use of piezoelectric bars and piezoelectric devices having various structures can be used depending on the desired application of the electro-mechanical transducer. For example, the piezoelectric device can have a planar shape where the width is approximately the same as the length.

[1061] While particular embodiments of the invention have been described with reference to piezoelectric ceramics, numerous other electro-mechanical devices may be used to implement the invention. For example, the electro-mechanical devices according to the invention may include electro-active polymers (EAP), voice coil transducers or other electro-magnetic device, or resonant eccentric rotating mass (HERM) devices.

[1062] While various embodiments of the invention have been described above, it should be understood that they have been presented by way of example only, and not limitation. Thus, the breadth and scope of the invention should not be limited by any of the above-described embodiments, but should be defined only in accordance with the following claims and their equivalence.

[1063] The previous description of the embodiments is provided to enable any person skilled in the art to make or use the invention. While various electro-mechanical transducers have been described including at least one electro-mechanical device including a piezoelectric substance, various other electro-mechanical devices may be utilized that can be configured to operate in multiple operational modes, each one of the multiple operational modes including a number of resonant modes. Other modifications to the overall structure of the electro-mechanical devices and arrangement of the selector-mechanical transducers can be made without departing from the spirit and scope of the invention.